Current Applied Physics 13 (2013) 1359–1364

Contents lists available at SciVerse ScienceDirect

Current Applied Physics

journal homepage: www.elsevier.com/locate/cap

Direct-current and radio-frequency characteristics of passivated AlGaN/GaN/Si high electron mobility transistors

H. Mosbahi [a], M. Gassoumi [a,d,*], Imen Saidi [c], Houcine Mejri [a], C. Gaquière [d], M.A. Zaidi [a,b], H. Maaref [a]

[a] Laboratoire de Micro-optoélectronique et Nanostructures, université de Monastir, Monastir 5000, Tunisia
[b] Faculté des Sciences Azolfi, Azolfi 11932, Saudi Arabia
[c] Laboratoire d'électronique et de microélectronique, Université de Monastir, Monastir 5000, Tunisia
[d] Institut d'Electronique et de Microélectronique et de Nanotechnologie (IEMN), Université des Sciences et Technologies de Lille, Avenue Poincaré, 59652 Villeneuve d'Ascq Cedex, France

ARTICLE INFO

Article history:
Received 9 November 2012
Received in revised form
2 April 2013
Accepted 7 April 2013
Available online 15 April 2013

Keywords:
AlGaN/GaN/Si HEMTs
DLTS
Pulsed current–voltage
Small-signal microwave
Passivation
Gate-lag and drain-lag
Electron traps

ABSTRACT

AlGaN/GaN/Si HEMTs grown by molecular beam epitaxy have been investigated using spectroscopy capacitance, direct and pulse current–voltage and small-signal microwave measurements. Passivation of the HEMT devices by SiO_2/SiN with NH_3 and N_2O pretreatments is made in order to reduce the trapping effects. As has been found from DLTS data, some of electron traps are eliminated after passivation. This has led to an improvement in the drain current. To describe the electron transport, we have developed a charge-control model by including the deep traps observed from DLTS experiments. The thermal and trapping effects have been, on the other hand, studied from a comparison between direct-current and pulsed conditions. As a result, a gate-lag and a drain-lag were revealed indicating the presence of deep lying centers in the gate-drain spacing. Finally, small-signal microwave results have shown that the radio-frequency parameters of the AlGaN/GaN/Si transistors are improved by SiO_2/SiN passivation and more increasingly with N_2O pretreatment.

1. Related works

During the last decades, AlGaN/GaN high electron mobility transistors (HEMTs) have attracted a great deal of interest for high-frequency and high-power applications [1,2]. The main reason is that nitride based materials have wide band gaps, large breakdown bias voltages and strong spontaneous and piezoelectric polarization fields as well as an efficient carrier transport [3]. As a result from the latter feature, a two-dimensional electron gas (2DEG) can occur at the AlGaN/GaN heterointerface with a relatively high density even without doping intentionally the barriers. Improvements have been achieved in performance of AlGaN-related heterostructure transistors by optimizing the growth conditions and design parameters. For instance, the insertion of a thin spacer in a transistor device is proved to reduce the alloy scattering and increases the mobility of carriers [4–6]. Also, a high aluminium content is recommended in order to increase polarization-induced charge densities and the electron confinement [7]. A considerable progress is obtained in this research field.

Defects and impurities are, however, unavoidable and hence can induce localized electronic states in the active layers. Most of them behave as trapping centers, leading to a limitation of the devices' performance. The origin of the active traps and especially their locations were characterized by different techniques [8–10]. They still remain controversial. This is due mainly to the variety of materials used to grow the heterostructures. On the other hand, for some applications, the use of Si as a substrate is revealed efficient to elaborate HEMTs with a low cost and an accurate integrating. However, the mismatch of AlGaN is higher for Si, which leads to a formation of defects in bulk and at the surfaces as well. The main obstacle to progress has been usually reducing the trap densities and at the same time improving the direct-current (DC) and the radio-frequency (RF) characteristics. As has been really found, AlGaN/GaN based heterostructures exhibit a much lower power at output. This phenomenon is called current slump and can cause a

* Corresponding author. Laboratoire de Micro-optoélectronique et Nanostructures, université de Monastir, Tunisia. Tel.: +216 73 500 276; fax: +216 73 500 278.
E-mail address: gassoumimalek@yahoo.fr (M. Gassoumi).

1567-1739/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.cap.2013.04.003

pronounced degradation in performance for HEMTs operating at large signal conditions. To overcome inconveniences and limitations of the trapping effects, surface passivation is recommended as a technological solution for AlGaN/GaN transistors. The passivation has been realized at first by using SiO_2 [11], MgO or Sc_2O_3 [12], SiN_x or Si_3N_4 [13–15] and Al_2O_3 [16,17]. Encouraging results were obtained for the AlGaN/GaN heterostructures investigated. This has been elucidated by a well-clear increase in the drain-current as well as in cut-off frequency and in microwave output power. To explain these features, it has been assumed that the surface traps are reduced and an additional stress-induced polarization charge is created due to passivation [18]. On the other hand, the DC/RF dispersion can be further reduced by using pretreatments prior to the passivation [19]. More recently, a two-step passivation has been employed by using SiN_x or SiO_x [20]. Compared to a one-step passivation, this approach is found to improve the electron transport in AlGaN/GaN HEMTs. Another mode of passivation has been proposed, which consists in in-situ and ex-situ deposited SiN_x [21]. Electrical and optical characterizations have been performed on passivated AlGaN/GaN heterostructures. As has been found, in-situ SiN_x passivation is a more efficient method to reduce electron traps and non radiative recombination centers.

In the present work reports on a study of unpassivated and passivated AlGaN/GaN/Si HEMTs using capacitance spectroscopy. Especially, two chemical species NH_3 and N_2O were used to realize the pretreatments prior passivation. As a main result, these pretreatments led to a suppression of some electron traps. For the same HEMT structures, we have also investigated the current–voltage and the radio-frequency characteristics at output. An attempt to correlate all of the results has been made in order to explain the origin of the electron transport improvement.

2. Deep levels characterization techniques

Deep-**L**evel **T**ransient **S**pectroscopy (DLTS) is an experimental tool for studying electrically active defects in semiconductors. DLTS establishes fundamental defect parameters and measures their concentration in the material. Some of the parameters are considered as defect "finger prints" used for their identifications and analysis.

DLTS investigates defects present in a space charge region of a simple electronic device. The most commonly used are Schottky diodes or p–n junctions. In the measurement process the steady-state diode reverse polarization voltage is disturbed by a voltage pulse. This voltage pulse reduces the electric field in the space charge region and allows free carriers from the semiconductor bulk to penetrate this region and recharge the defects causing their non-equilibrium charge state. After the pulse, when the voltage returns to its steady-state value, the defects start to emit trapped carriers due to the thermal emission process. The technique observes the device space charge region capacitance where the defect charge state recovery causes the capacitance transient. The voltage pulses followed by the defect charge state recovery are cycled allowing an application of different signal processing methods for defect recharging process analysis [22].

The DLTS technique has a higher sensitivity than almost any other semiconductor diagnostic technique.

2.1. Conventional DLTS

In our laboratory we used a conventional DLTS, the capacitance transients are investigated by double box-car averaging technique when the sample temperature is slowly varied (usually in a range from liquid nitrogen temperature (4 K) to room temperature 325 K or above). The equipment reference frequency is the voltage pulse repetition rate. In the conventional DLTS method this frequency multiplied by some constant is called the "rate window". When during the sample temperature variation the emission rate of carriers from some defect equals to the rate window one obtains in the spectrum a peak. By setting up different rate windows in subsequent DLTS spectra measurements one obtains different temperatures at which some particular peak appears. Having a set of the emission rate and corresponding temperature pairs one can make an Arrhenius plot, which allows for the deduction of defect activation energy for the thermal emission process. Usually this energy together with the plot intercept value are defect parameters used for its identification or analysis. On samples with low free carrier density conductance transients have also been used for a DLTS analysis.

3. DLTS experiments

The AlGaN/GaN HEMTs under investigation are grown on silicon (111) substrate by using molecular beam epitaxy (MBE) (present some high purity). The active layers consist in a 500 nm thick of undoped AlN/AlGaN buffer, a 1.8 μm undoped GaN channel, a 23 nm thick of undoped $Al_{0.26}Ga_{0.74}N$ barrier and a 1 nm n^+-GaN cap layer. The device processing is made following conventional HEMT fabrication steps. The ohmic contact pads are patterned using e-beam lithography. Hereafter, the metallization by means of evaporated 12/200/40/100 nm Ti/Al/Ni/Au is deposited at 900 °C during 30 s. The Schottky gate is realized using 100/150 nm Mo/Au layers. On the other hand, the AlGaN/GaN HEMTs are passivated by 100/50 nm SiO_2/SiN with NH_3 and N_2O pretreatments. Deep level transient spectroscopy has been used as a technique to characterize the electron traps in the AlGaN/GaN/Si heterostructures. Measurements were performed using double lock-in detection and a PAR 410 capacitance meter and recorded in the 20–325 K temperature range. Small signal characterization of the devices is carried out by wafer *S* parameter measurements with use of an HP 8510 network analyzer.

Capacitance spectroscopy measurements have been performed on the samples prepared. Fig. 1 shows the DLTS signal of an unpassivated AlGaN/GaN/Si HEMT. As can be noticed, the spectrum is composed of four overlapped peaks, labeled A1–A4 and which

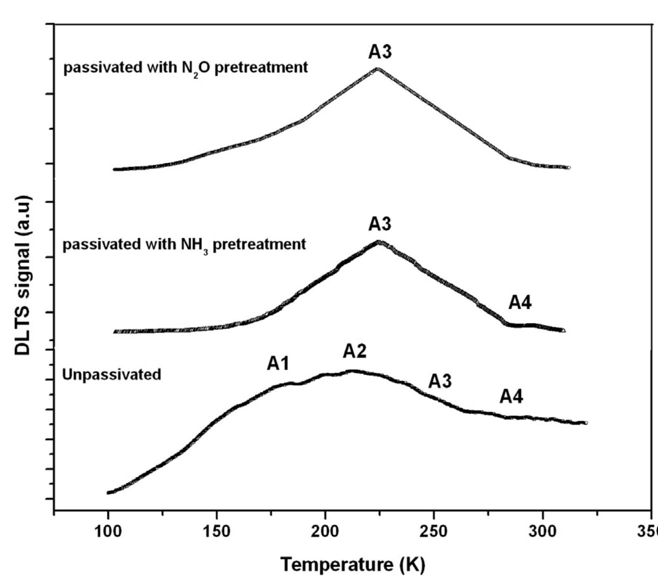

Fig. 1. DLTS spectra of the AlGaN/GaN/Si HEMTs. The symbols A1, A2, A3 and A4 refer to the electron traps observed in the 100–325 K temperature range.